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Emitted radiation from a two temperature advective flow around black holes

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Abstract : Low angular momentum accretion flows very often have centrifugal pressure supported standing shock waves which can accelerate flow particles. The accelerated particles in turn, emit synchrotron radiation in presence of magnetic fields. Efficient cooling of the electrons reduces its temperature in comparison to the protons. In this communication, we assume two temperature flows to explore this property of shocks and present an example of the emitted radiation spectrum.

Keywords : Black holes, radiative transfer, hydrodynamics, shock waves.

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1. Introduction

It is more than fifty years since the study of the accretion flows on to gravitating compact objects began. Bondi [1] first showed that spherically symmetric matter would pass through a sonic sphere before falling on a sufficiently compact object. However, such matter has a large radial velocity v and from the continuity equation

$$\rho v r^2 = \text{constant}, \tag{1}$$

it is clear that the density becomes very low close to a black hole. As a result, the flow has a very low radiation efficiency. To improve the efficiency, several important steps have been adopted. First, Shvartsman [2] introduced magnetic dissipation and Shapiro [3,4] found that this dissipation enhanced the luminosity by a significant amount. However, this was still not sufficient to explain quasar luminosity and Chang and Ostriker [5] and Kazanas and Elison [6] resorted to introducing accretion shocks where the temperature and density would be enhanced and the radiation efficiency is also increased. Chakrabarti [7] showed that centrifugal barrier in a low angular momentum accretion flow can produce stable shocks for a wide range of parameter space provided the flow has specific angular momentum everywhere small compared to the Keplerian value. This work was further amplified by Chakrabarti and Wiita [8] and Chakrabarti and Titarchuk [9] who showed that shocks could play a major role in determining the spectrum of the emitted radiation. Particularly important is that the post-shock region, which is the repository of hot electrons, can easily inverse Comptonize photons from a Keplerian disk located in the pre-shock region and the power-law component of the flow may be formed easily without taking resort to any hypothetical electron cloud. In effect, the post-shock region in between the horizon and the shock behaves like a boundary layer where the flow dissipates its gravitational energy. This region is known as CENBOL (Centrifugal pressure supported Boundary Layer).

However, the shocks have another important role. It is well known that the cosmic rays are produced by shock acceleration [10–12]. These shocks are in general of transient nature and still play an important role in shaping the spectrum. Hence, it is likely that the *standing shocks*, through which all the accreting matter *pass* be-

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fore entering into a black hole, or forming a jet, should be important to energize matter. In the present communication, we are interested to identify the signature of energetic matter in the post-shock region.

In Section 2, we present the basic equations and the relevant parameters for the problem. In Section 3, we present emergent spectra for a typical case and identify each part of the spectrum. We also discuss their significance. Finally, in Section 4, we present concluding remarks.

2. Basic equations and relevant parameters

The velocity profile of the inflow is described by the adiabatic Bondi solution. This gives

$$u(X) = X^{-1/2} \tag{2}$$

where X is the radial distance in units of Schwarzschild radius, $r_g = 2GM/c^2$, c is the velocity of light, G is the gravitational constant and M is the mass of central black hole. The electron number density, determined from the mass conservation law assuming pure hydrogen, is given by

$$n(X) = \frac{\dot{M}}{4\pi m_p X^2 v(X)} \tag{3}$$

where, the geometric factor 4π arises because we are assuming spherical accretion, $\dot{M}$ is the mass accretion rate and m_p is the proton mass. In presence of pure hydrogen, Thomson scattering will be the most dominating scattering process and the corresponding optical depth,

$$\tau(X) = \dot{M} X^{-1/2} \tag{4}$$

where $\dot{m}$ is the mass accretion rate in units of Eddington rate. We calculate magnetic field from equipartition between gravitational energy density and magnetic energy density *i.e.*,

$$\frac{B^2}{8\pi} = \frac{GM\rho}{X} \tag{5}$$

Using eqs. (2) and (3), the energy balance equations for protons and electrons can be written as (see also [13]),

$$\frac{dT_p}{dX} + \frac{T_p}{X} + \frac{4\pi\mu m_p}{k\dot{M}}\frac{2}{3}X^2(\Gamma_p - \Lambda_p) = 0, \tag{6a}$$

$$\frac{dT_e}{dX} + \frac{3}{2}(\gamma - 1)\frac{T_e}{X} + \frac{4\pi\mu m_p}{k\dot{M}}(\gamma - 1)X^2(\Gamma_e - \Lambda_e) = 0, \tag{6b}$$

where γ is 5/3 for non-relativistic electron temperatures ($T_e \leq m_e c^2/k$) and 4/3 for relativistic electron temperatures ($T_e > m_e c^2/k$). Here, μ is the mean molecular weight which is 0.5 for hydrogen, k is the Boltzmann constant. Since proton is much heavier than electron, T_p always remains in the non-relativistic regime. Γ and Λ contain contributions from all the heating and cooling processes respectively.

3. Forms of heating and cooling terms

First of all, we neglect heating due to dissipation for the protons. Protons are assumed to lose energy through Coulomb interaction Γ_{ep} and inverse bremsstrahlung Λ_{ib}. So,

$$\Lambda_p = \Gamma_{ep} + \Lambda_{ib}. \tag{7}$$

Here, the subscript p represents protons. The effect of Λ_{ib} is generally much smaller than Γ_{ep}. The loss of energy by electrons due to various cooling processes are compensated by electron proton coupling. This causes cooling of the electrons.

$$\Gamma_{ep} = 1.6 \times 10^{-13}\frac{k\sqrt{m_e}\ln\Lambda_0}{m_n}n^2(T_p - T_e)T_e^{-3/2}, \tag{8}$$

where $\ln\Lambda_0$ is the Coulomb logarithm, m_p and m_e are the masses of protons and electrons respectively. Electrons are heated through this Coulomb coupling. That is,

$$\Gamma_e = \Gamma_{ep} \tag{9}$$

subscript e represents electrons. $\Gamma_p = 0$ in our case.

Cooling terms for electrons include bremsstrahlung Λ_b, cyclo-synchrotron Λ_{cs}, and Comptonization Λ_{mc} of the soft photons due to cyclo-synchrotron radiation. For the time being, we ignore any Keplerian flow on the equatorial plane which could also supply soft photons. The net cooling of the electrons is

$$\Lambda_e = \Lambda_b + \Lambda_{cs} + \Lambda_{mc}. \tag{10}$$

An explicit expressions for the cooling terms are :

$$\Lambda_{ib} = 1.4\times10^{-27}n^2\left(\frac{m_e}{m_n}T_p\right)^{1/2} \tag{11}$$

$$\Lambda_b = 1.4 \times 10^{-27} n^2 T_e^{1/2}(1 + 4.4 \times 10^{-10} T_e), \tag{12}$$

$$\Lambda_{cs} = \frac{2\pi}{3c^2} kT_e(X) \frac{\nu_a^3}{X}, \tag{13}$$

where ν_a is the critical frequency at which the self-absorbed synchrotron radiation spectrum is peaked and it can be determined from the relation

$$\nu_a = \frac{3}{2} \nu_0 \theta_e^2 x_m, \tag{14}$$

where

$$\nu_0 = 2.8 \times 10^6 B, \tag{15a}$$

$$\theta_e = \frac{kT_e}{m_e c^2}, \tag{15b}$$

and x_m is determined from the transcendental equations,

$$\exp(1.8899\ x_m^{1/3}) = 2.49 \times 10^{-10} \frac{4\pi n x}{B} \frac{1}{\theta_e^3 K_2(1/\theta_e)}$$

$$\times \left(\frac{1}{x_m^{7/6}} + \frac{0.40}{x_m^{17/12}} + \frac{0.5316}{x_m^{5/3}} \right). \tag{16}$$

The Comptonized spectrum due to Cyclotron photons are obtained from :

$$\Lambda_{mc} = \Lambda_{cs} \left[\eta_1 \left\{ 1 - \left(\frac{x_c}{3\theta_e} \right)^{\eta_2} \right\} \right], \tag{17}$$

where $\eta_1 = \frac{P(A-1)}{(1-PA)}, P = 1 - \exp(1 - \tau_{es})$ is the probability that an escaping photon is scattered, while $A = 1 + 4\theta_e + 16\theta_e^2$ is the mean amplification factor in the energy of a scattered photon when the scattering electrons have a Maxwellian velocity distribution of temperature $\theta_e, \eta_2 = 1 - \frac{\ln P}{\ln A}$ and $x_c = h\nu_a / m_e c^2$.

4. Solution procedure

For a given case, we fix the outer boundary at a large distance (say, $10^6 r_g$) and supply matter (both electrons and protons) with the same temperature (say, $T_p = T_e = 10^6$ K). Radial dependence of velocity and density is chosen to be those of freely falling matter. We then use Runge-Kutta method to integrate eqs. (6a) and (6b) simultaneously to obtain the electron and proton temperatures. After we obtained density and temperature at any point, we compute the radiation emitted by the flow through bremsstrahlung and synchrotron radiation. These low energy photons are then inverse Comptonized by the hot electrons in the flow. We followed the procedures presented in Chakrabarti and Titarchuk [9] while computing the Comptonized spectrum. At the end, we add the contributions to get the net photon emissions from the flow. The geometry of the flow is chosen to be conical. The angle Θ subtended by the flow with the z-axis is chosen to be a parameter. For simplicity, we also choose the shock location X_s and the compression ratio R as free parameters. The shock of compression ratio R causes the formation of power-law electrons of slope $p = (R + 2)/(R - 1)$ [10,11]. These power-law slope electrons produce a power-law slope in the synchrotron emission $q = (1 - p)/2$ [12]. The power-law electrons have energy minimum at $\varepsilon_{min} = 1$, and have energy maximum at ε_{max} obtained self-consistently by conserving the number of power-law electrons and by computing the number of scattering that the electrons undergo inside the disk before they escape. (Here, ε is the bulk Lorentz factor of the electrons.) In a realistic flow, not all of the incoming matter is expected to pass through the accretion shock, and we assume that the percentage of electrons ς having power-law index to be a free parameter. This work is thus of an exploratory nature.

While including the synchrotron radiation, we have taken special care to incorporate the synchrotron self-absorption by the emitting media itself. This self-absorption occurs when the medium, which is emitting the synchrotron radiation itself becomes optically thick and starts emitting black body. This happens at low frequency side of the spectrum, which is computed self-consistently.

We can vary parameters such as $\Theta, X_s, R, \varsigma$ and $m = \frac{\dot{M}}{\dot{M}_{Edd}}$, the accretion rate of the flow in units of the Eddington rate $\dot{M}_{Edd}$. In this *Rapid Communication*, we present a typical spectrum assuming a black hole of mass $10 M_\odot$.

5. Results and interpretations

Figure 1 shows the variation of the electron and proton temperatures (T_e and T_p respectively) when $\dot{m} = 0.0005$, $R = 3.9$, $\Theta = 77°$, $\varsigma = 0.7$ and $X_s = 10$ as a function of the radial distance X (measured in units of the Schwarzschild radius r_g). The location of the shock depends on the specific angular momentum, thus supplying X_s instead of specific angular momentum, is consistent. Both the axis of the plot is in logarithmic scale. It is clear that in the absence of strong electron heating by Coulomb coupling alone, the electrons start becoming cooler closer to the black hole when the number density gets higher. Higher number density increases the cooling for $X \lesssim 300$. Very close to the black hole, especially after the shock at $X = X_s = 10$, the splitting is dramatic and electrons become very much cooler. With our parameters, below $X \sim X_c = 5.8$, the cooling is so strong that Comptonization procedure breaks down. We left the temperature to be same as that of a keplonian disk for simplicity.

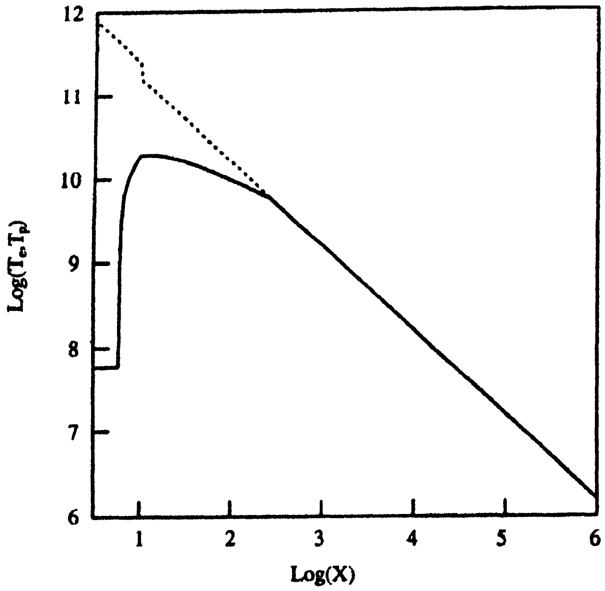

Figure 1. Temperature distribution of protons and electrons as a function of radial distance from the black hole.

In Figure 2, we present a typical spectrum with all the contributions from the accretion flow. The parameters chosen are the same as above. Here, different curves are marked with a number. The curve marked '1' is due to synchrotron emission from the CENBOL region due to Maxwell electrons. The curve marked '2' is that due to the power-law electrons in CENBOL. The curve marked '3' is the synchrotron emission from the pre-shock part of the accretion flow. The reason why the power is higher and at a higher frequency is that the volume of the pre-shock region is much larger and the average temperature of the electrons is also reasonably large in the pre-shock region. The curve marked '4' gives the Comptonized spectra of the synchrotron radiation from the pre-shock accretion flow. The curve marked '5' which is really made up of two pieces, one (up to the self-absorption frequency ν_a) of a black-body power-law of slope -2, and the other of a power-law of slope same as curve '2' due to power-law electrons, gives the net synchrotron emission from the CENBOL region after the self-absorption is taken care of. The curve marked '6' is the Comptonization of the black-body part of the soft photons emitted by CENBOL (*i.e.*, the photons emitted with $\nu < \nu_a$, see curve 5). The curve marked '7' is the Comptonization of the soft synchrotron photons emitted from the power-law electrons ($\nu > \nu_a$ of curve 5). The curve marked '8' is the total Compton spectra from the pre-shock as well as the post-shock regions.

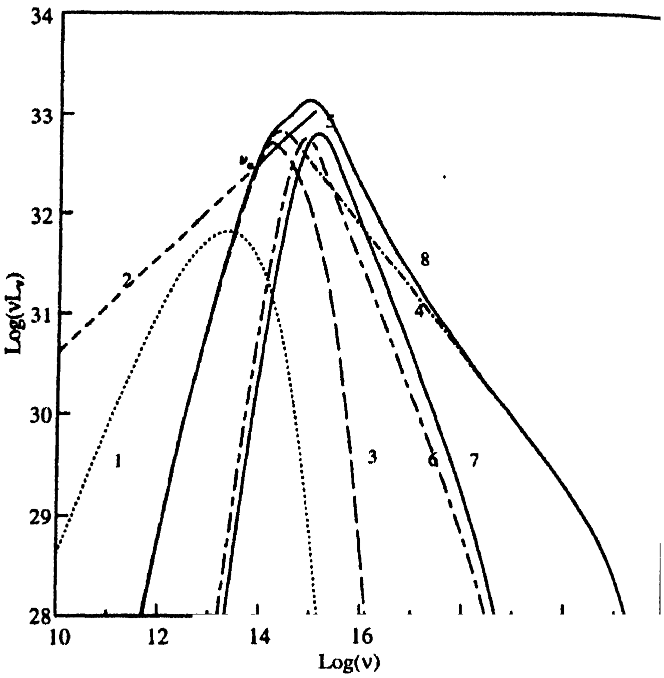

Figure 2. A typical spectrum from an accretion disk is shown with its components. See text for details.

It is clear that the power-law electrons, which are the hall-mark of the shock in accretion can leave its signature on the emitted spectrum, as is evidenced from the power-law part of the spectrum near log (ν) ~14–15. Around log (ν) ~16, the power-law photons are produced mainly due to Comptonization of the CENBOL photons, while the power-law around log (ν) ~18–20 is mainly due to the Comptonization of the photons from the pre-shock region. Thus, separate regions of the spectrum can be identified with separate physical processes inside an accretion disk.

6. Concluding remarks

In this communication, we have explored the way a shock in an accretion flow may be identified. We considered the soft photons due to bremsstrahlung and synchrotron radiation as the seed photons for the Comptonization. We also included the shock acceleration of the electrons and their effect on the emitted spectrum. We have incorporated the splitting of temperature of the electrons and protons due to radiative processes.

Our conclusion is that there are several ways a shock may be distinguished in the spectrum. At a strong shock, the power-law electrons are produced with a very high ε_{max} and that produces a power-law feature in the spectrum. When the accretion rate is increased, the post-shock region is cooled down due to high synchrotron radiation, and the post-shock radiation produces a bump at a lower energy than what is produced by the pre-shock flow. With a rise in accretion rate it becomes difficult to cool down the pre-shock photons. This makes the spectrum harder at high energies with a higher turn-over frequency.

In Chakrabarti and Titarchuk [9] soft photons due to a Keplerian disk was responsible to cool down the post-shock region. In the present communication, we deviate from that paper in the sense that we assume that the Keplerian disk is either located very far away, or non-existent. The soft photons are locally generated due to thermal and magnetic bremsstrahlung processes. In future, we shall compare these results with observed spectra in order to pinpoint signatures of a shock in an accretion flow. The presence of an accretion disk of rate 0.0005 would produce a very weak bump at around 10^{18-19} Hz, very far away from the power-law electron induced spectral-bump discussed here. So the effect is still visible.

The outflow that is derived from a CENBOL itself can have shocks in jets. Thus, there could be signatures of outflows and post-shock regions of the outflow as well. However, we believe that this effect would not be very important since the emitting volume would be much smaller compared to the emitting volume of the accretion disk. We shall explore this aspect of the problem in near future.

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